Telerobotics: A Simulation Facility for University Research

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ABSTRACT

An experimental telerobotics (TR) simulation is described suitable for studying human operator (H.O.) performance. Simple manipulator pick-and-place and tracking tasks allowed quantitative comparison of a number of calligraphic display viewing conditions.

A number of control modes could be compared in this TR simulation, including displacement, rate and acceleratory control using position and force joysticks. A homeomorphic controller turned out to be no better than joysticks; the adaptive properties of the H.O. can apparently permit quite good control over a variety of controller configurations and control modes. Training by optimal control example seemed helpful in preliminary experiments.

An introduced communication delay was found to produce decrease in performance. In considerable part, this difficulty could be compensated for by preview control information. That neurological control of normal human movement contains a sampled data period of 0.2 seconds may relate to this robustness of H.O. control to delay.

The Ames-Berkeley enhanced perspective display was utilized in conjunction with an experimental helmet mounted display system (HMD) that provided stereoscopic enhanced views. Two degree-of-freedom rotations of the head were measured with a Helmholtz coil instrument and these angles used to compute a directional conical window into a 3-D simulation. The vector elements within the window were then transformed by projective geometry calculations to an intermediate stereoscopic display, received by two video cameras and imaged onto the HMD mini-display units (one-inch CRT video receivers) mounted on the helmet.

INTRODUCTION

A telerobotic, TR, system is defined as a distant robot with vision and manipulator and/or mobility subsystems controlled by a human operator, HO. The HO is informed mainly by a visual display, but also by other sensors and other sensory displays, i.e. auditory, force or tactile. His control can be direct via joysticks, or supervisory via command and control primitives effected by partially autonomous robotic functions. Delays and bandwidth limitations in communication are key problems, complicating display and control (Stark, Kim, Tendick, et al. 1996)

The research presented here was initially carried out by the students taking a graduate control course, ME 210 "Biological Control Systems: Telerobotics."

EXPERIMENTAL SET-UP FOR THREE-AXIS PICK-AND-PLACE TASKS

A teleoperation simulator constructed with a display, joysticks, and a computer enabled three-axis pick-and-place tasks to be performed and various display and control conditions evaluated (Figure 1). A vector display system (Hewlett-Packard 1345A) was used for fast vector drawing and updating with high resolution. In our experiments, displacement joysticks were mainly used, although in one experiment a force joystick was used to compare with a displacement joystick. An LSI-11/23 computer with the RT-11 operating system computer was connected to the joystick outputs through 12-bit A/D converters, and to the vector display system through a 16-bit parallel I/O port.

A typical presentation on the display screen for three-axis pick-and-place tasks included a cylindrical manipulator, objects to pick up, and boxes in which to place them, all displayed in perspective (Figure 2). Since perspective projection alone is not sufficient to present three-dimensional information on the two-dimensional screen, a grid representing a horizontal base plane and reference lines indicating vertical separations from the base plane are also presented (Ellis, Kim, McGreevy, Tyler and Stark, 1985; Kim, Ellis, Tyler and Stark, 1985). The human operator controlled the manipulator on the display using two joysticks to pick up each object with the manipulator gripper and place it in the corresponding box. One hand, using two axes of one joystick, controls the gripper position for the two axes parallel to the horizontal base plane (grid). The other hand, using one axis of the other joystick, controls the gripper position for the third axis (vertical height) perpendicular to the base plane. Picking up an object is accomplished by touching an object with the manipulator gripper. Likewise, placing an object is accomplished by touching the correct box with the manipulator gripper.

Puma Arm Simulator

In addition to the cylindrical manipulator simulation, the kinematics and dynamics a six degrees-of-freedom Puma robot arm were simulated. Each of these degrees of freedom were controlled simultaneously using two joysticks. Although no experiments have yet been performed with the puma simulation, it is hoped that it will be a step toward experiments with more complex manipulators. A low-bandwidth telephone connection to control two Puma arms at Jet Propulsion Labs in Pasadena is planned. The simulation will allow prediction of the robots' motion to provide a preview display to help overcome the communication delays inherent in such a low bandwidth connection, or as in transmissions to manipulators in space.

Figure 1. Experimental Arrangement

Figure 2. Ames-Berkeley Visual Enhancement Display

CONTROL MODE EXPERIMENTS

Position and rate controls are the two common manual control modes for controlling telemanipulators with joysticks (or hand controllers) (Johnsen & Corliss, 1971; Heer, 1973). In the position control the joystick command indicates the desired end effector position of the manipulator, whereas in the rate control the joystick command indicates the desired end effector velocity.

In our three-axis pick-and-place tasks, the human operator controls the manipulator hand position in the robot base Cartesian coordinate by using three axes of the two displacement joysticks. In pure (or ideal) position control, the system transfer function from the joystick displacement input to the actual manipulator hand position output is a constant gain G_p for each axis. In pure rate control, the system transfer function is a single integrator G_v/s for each axis. In the rate control, a 5% dead-band nonlinearity is introduced before the pure integrator in order to inhibit the drift problem associated with the pure integrator.
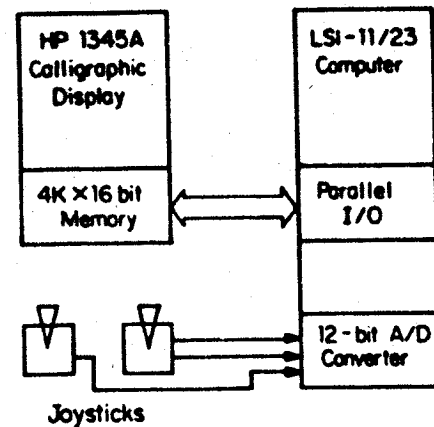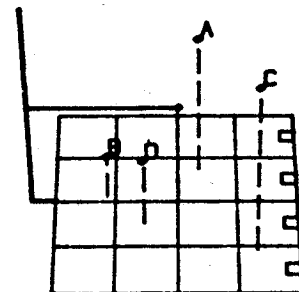
Comparison of pure position and rate controls

Three-axis pick-and-place tasks were performed with both pure position and rate control modes for various gains (Figure 3). The mean completion time plot clearly shows that pick-and-place performance with pure position control (mean completion time 2.9 seconds at $G_x = 2$) was about 1.5 times faster than that of the pure rate control (mean completion time 4.5 seconds at $G_v = 4$).

Trajectories of Joystick and Manipulator Movements

In order to examine why the position control performed better than the rate control, several trajectories of the joystick displacement input and the manipulator hand position output during the pick-and-place operation were observed. Typical trajectories from the start of trying to pick up an object to its accomplishment were plotted to illustrate position, rate, and acceleration controls (Figure 4). Components only for the x-axis (side-to-side) are plotted, since components for the other two axes are similar. Observation of several trajectories indicates that a precise re-positioning of the manipulator hand is achieved by a combination of quick step re-positioning operations and slow smooth movement operations. In position control one quick step re-positioning of the manipulator hand from one position to another requires one joystick pull or push operation, whereas in the rate control it requires a pair of operations: pull-and-push or push-and-pull operations (Figure 4). This is a major reason why the position control yielded better performance than the rate control for our pick-and-place tasks. It should be noted, however, that the pick-and-place task is a positioning task. If the task is following a target with a constant velocity, then velocity (rate) control would perform better.

Acceleration Control

Three-axis pick-and-place tasks were also tried with acceleration control. It turned out, however, acceleration control was not adequate to perform stable, safe pick-and-place operations. In acceleration control, the manipulator tends to move almost all the time even though the joystick is at the center position. Note that in pure rate control, the manipulator does not move when the joystick is at the center position regardless of previous history of the joystick displacement.

Human Adaptation to Gain Change

Mean completion time did not change much for the various gains tested (Figure 3), which means that the human operator adapted well to the gain change (McRuer, et al. 1965; Young, 1969; Stark, 1968). Both lower and higher gains relative to the optimal gains caused slight increase in the mean completion time. A reason of slightly longer mean completion times with lower gains is because lower gains demand wider joystick displacements and it takes longer for the finger or hand to displace the joystick wider. A reason for slightly longer mean completion times with higher gains is that higher gains demand more minute joystick displacements, degrading effective resolution of the joystick control. An additional major reason for longer mean completion times with lower gains for the rate control is due to the velocity limit.
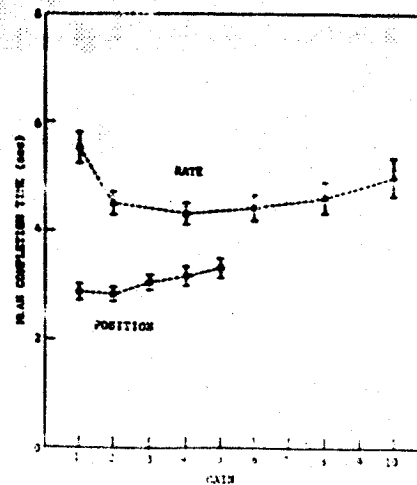

Figure 3. Performance Comparison of Position and Rate Control. Note low sensitivity to gain change
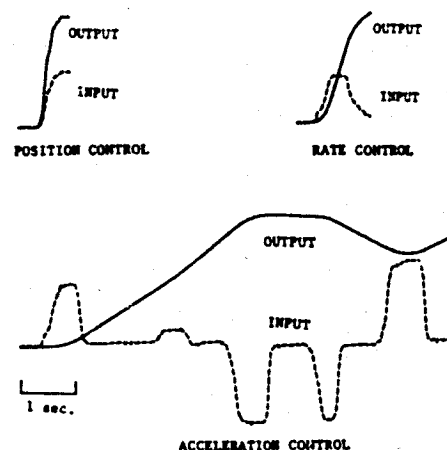

Figure 4. Position, Rate and Acceleration Control. Typical trajectories of HO control and resultant manipulator output illustrate these control modes

Force joystick

The two common joystick types are the displacement and force joysticks. The output of the displacement joystick is proportional to the joystick displacement, whereas the output of the force joystick (isometric or stiff joystick) is proportional to the force applied by the human operator. The advantage of the force joystick is that it requires only minute joystick displacements (a few micrometers) in contrast with the displacement joystick (a few centimeters).

Pick-and-place tasks were performed for pure position and rate controls with displacement and force joysticks. The experimental results for two subjects (Figure 5) shows that in the rate control, task performance with force joystick was significantly faster than that with displacement joystick. This is mainly because the force joystick senses the applied force directly, requiring only very minute joystick displacements. In the position control, however, the force joystick performed no better than the displacement joystick. In fact, all three subjects preferred to use the displacement joystick in this mode, since the force joystick required more force to be applied than the displacement joystick, especially when the manipulator hand is to be positioned far away from the initial center position. Position control also performed better than the rate control regardless of joystick types, and furthermore the position control with the displacement joystick performed best for our pick-and-place tasks (Figure 5).
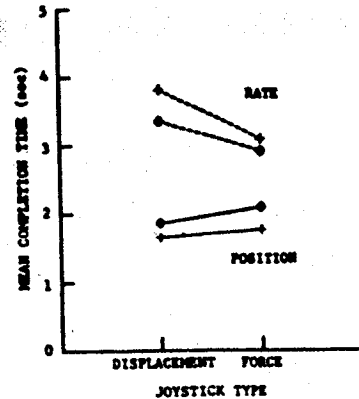

Figure 5. Displacement and Force Joystick Control. Note adaptive ability of HO to utilize these different joysticks. Position control is superior to rate control in the particular task studied. Two subjects: diamond (WK), cross (MT).

Resolution

The experimental results demonstrate the superiority of position control when the telemanipulator has a sufficiently small work space (Figures 3, 4, & 5). Note that our three-axis pick-and-place tasks used in this experiment implicitly assumes that the manipulator work space is small or at least not very large, since our task allows the human operator to perform successful pick-and-place operations with a display showing the entire work space on the screen. Examples of small work space telemanipulators can be found in nuclear reactor teleoperators, surgical micro-telerobots, or small dexterous telerobotic hands. Position control can also be utilized during proximity operations in conjunction with the force-selecting joysticks for enhanced telepresence (Bejczy, 1980). When the telemanipulator's work space is very large as compared to human operator's control space, position control of the entire work space suffers from poor resolution since human operator's control space must be greatly up-scaled to accommodate the telemanipulator's large work space (Flatau, 1973). One way of solving this poor resolution problem in position control is using indexing Johnsen & Corliss, 1971; Argonne National Lab, 1967). In the indexed position control mode, the control stick gain is selected so that the full displacement range of the control stick can cover only a small portion of the manipulator work space, and large movements of the manipulator hand can be made by successive uses of an indexing trigger mounted on the control stick. Note, however, that rate control can inherently provide any higher degree of resolution by mere change of control stick gain without use of indexing.

HOMEOMORPHIC CONTROLLER

Most of our pick-and-place and tracking experiments were performed with joysticks as the input device through which the human operator controlled the simulated manipulator. The operator's movements when using joysticks are non-homeomorphic, so that the movements he must make to produce a desired manipulator response do not match the movement of the manipulator end effector. Thus, he must mentally convert the desired end effector position to Cartesian coordinates and use the joysticks to input these coordinates.

To attempt to study whether a truly homeomorphic input device could improve performance in tracking tasks, an apparatus of identical form to our simulated cylindrical manipulator was built. A vertical rod was supported by bearings on the base to allow rotation, theta. A counterweighted horizontal arm was attached to the rod with sliding bearings to permit rotation and translation in the r and z axes respectively. The human operator could control position through a handle on the end of the arm corresponding to the end effector of the simulated manipulator. Potentiometers measured movement in each axis to determine input r, theta, and z. The LSI-11/23 computer read these values through A/D channels and displayed the manipulator in the identical position.

Three-dimensional tracking experiments were performed with the homeomorphic controller and with joysticks for gains varying from 1 to 5 to compare performance (Figure 6). The results do not show a significant difference between the homeomorphic controller and joysticks over the range of gain values. Although the larger movements required for the homeomorphic controller, with greater inertia and friction than the joystick, may have limited performance, we believe that human adaptability minimizes its advantages.

TRAINING BY OPTIMAL CONTROL EXAMPLE

A simplified simulation of the manned maneuvering unit, MMU, enabled study of training of human control performance (Jordan, 1985). Only three translatory degrees-of-freedom, x, y and z, were used. Thrusters generating pulses of acceleratory control were controlled via a keyboard and the task was to accelerate simultaneously in x, y and z to a maximum velocity, transit to the desired new location, and decelerate again simultaneously. Two displays were used --a perspective display of a minified model of the MMU, or two two-dimensional projectors of that model with a small inset of the perspective display.

Subjects generally performed poorly during the few hundred seconds allowed for the tasks (upper panels, Figure 7). It was decided to allow the subjects to view this control problem carried out by a simple optimal control algorithm (see middle panel, Figure 7). This experience was of considerable help and several subjects then performed quite well (bottom panel, Figure 7).

This experiment, learning-by-example, illustrates a strategy that perhaps may be effective in more complex and realistic tasks as well.

Figure 6. Homeomorphic Controller. Note similar low sensitivities to gain for all three axes. (x-axis, diamonds; y-axis, crosses; and z-axis, squares)

COMMUNICATION DELAY AND PREVIEW

Communication delay is a significant constraint in human performance in controlling a remote manipulator. It has been shown (Sheridan et al, 1964, 1966; Tomizuka and Whitney, 1976) that preview information can be used to improve performance. Stark et al (1986) demonstrated that preview can significantly reduce error in tracking experiments with imposed delay.

Experiments were performed to investigate whether a preview display could improve performance in pick-and-place tasks with delay. A single bright diamond-shaped cursor was added to the display to represent current joystick position. This was a perfect prediction of what the end effector position would be after the delay interval. Thus, the task was the same as if there were no delay, except that the HO had to wait one delay period for confirmation that a target had been touched or correctly placed (in the non-previewed display, the target letter was doubled when picked up, and became single again when placed in the correct box).

Preview improved performance at delays up to 4 seconds so that it was almost as good as for a small delay of 0 2 seconds (Figure 9). While task completion time in the delayed condition increased greatly with delay, there was only a small increase in the preview case. This is because the H.O. must compensate for delays by using a "move-
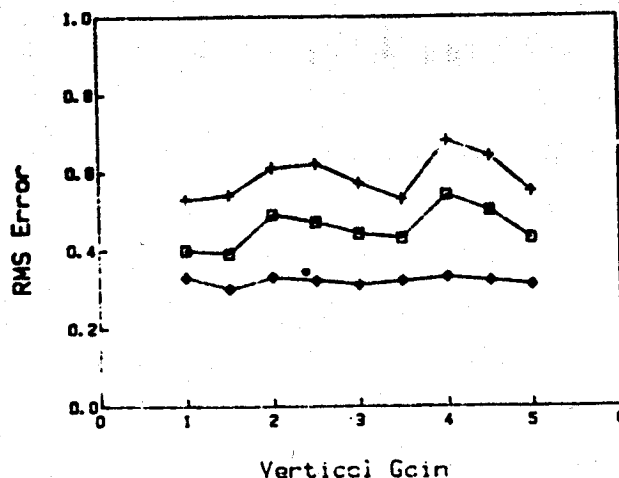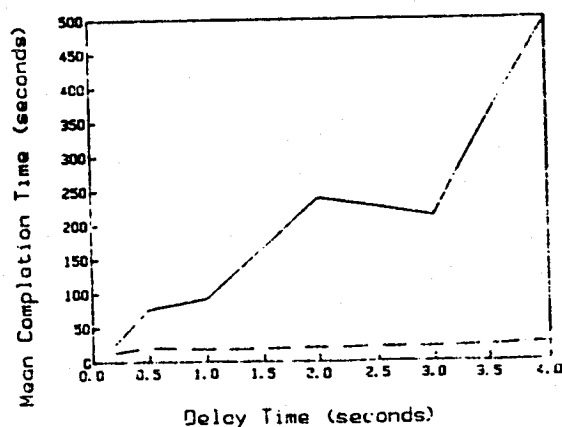
Figure 9. Performance affected by delays and by preview control mode. Note severe adverse influence delay and beneficial effect of preview control in this pick-and-place task.
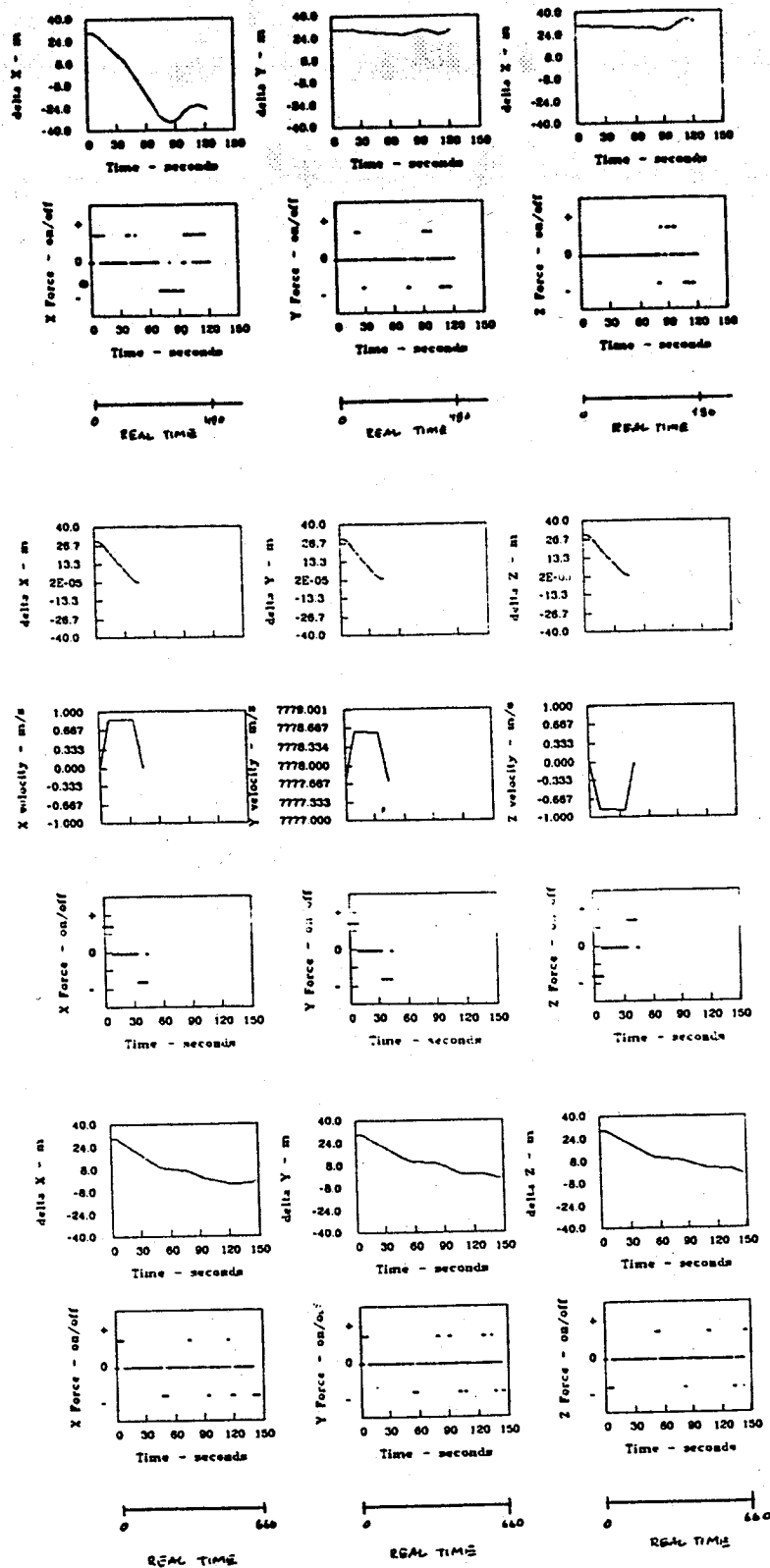
Figure 7. Training by Example. MMV control in three axes showing displacement, forces, and velocity for automatic control. Note improvement after training

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and-wait" strategy, making a joystick movement and waiting to see the resultant end effector movement. In the preview case, this strategy is only necessary when very close to the target or box to wait for confirmation that the goal has indeed been touched.

<div align="center">HELMET MOUNTED DISPLAY DESIGN</div>

Motivation

The motivation of the HMD system is to provide the human operator with a telepresence feeling that he is actually in the remote site and controls the telemanipulator directly. The HMD system detects the human operator's head motion, and controls the remote stereo camera accordingly. In our current system, the remote telemanipulation task environment is simulated and the pictures for the display are generated by the computer.

Head Orientation Sensors

A two-axis magnetic Helmholtz coil arrangement was used as a head orientation sensing device, to detect horizontal and vertical head rotations (Figure 9). By assuming that the pan and tilt angles of a remote stereo camera are controlled in accordance with the horizontal and vertical head rotations, respectively, the computer generates the corresponding stereo picture for the HMD. The head orientation sensing device is composed of a search (sensing) coil mounted on or beneath the helmet and two pairs of field coils fixed with respect to human operator's control station. The right-left pair
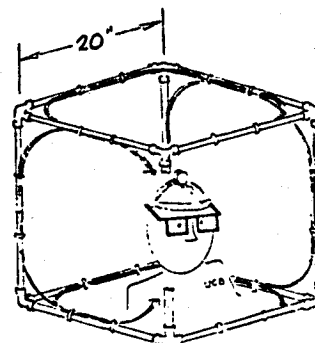
of the field coil generates the horizontal magnetic flux of a 50 KHz square wave. The up-down pair of the field coil generates the vertical magnetic flux of a 75 KHz square wave. The search coil detects the induced magnetic flux, which is amplified and separated into 50 and 75 KHz components. The magnitude of each frequency component depends upon the orientation of the search coil with respect to the corresponding field coil (Duffy, 1995).

Figure 9. Head Orientation Sensor Device

LCD Display

An early configuration of the HMD had a flat-panel LCD (liquid crystal display) screen (a commercially available portable LCD television) mounted on the helmet for the display (Figure 10). However, the picture quality of the LCD screen was poor due not only to low resolution but also to poor contrast.
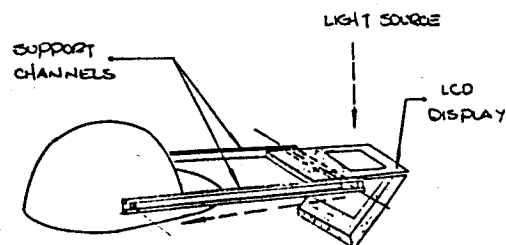
Figure 10. Early HMD Design with LCD Screen

CRT Display

A new design of the HMD that we currently have, mounts a pair of Sony viewfinders (Model VF-208) on the helmet (Figure 11). Each viewfinder has a 1-inch CRT (cathode ray tube) screen and a converging lens through which the human operator views the CRT screen. The computer-generated stereo picture pair (stereogram) is displayed on the CRT screens; one for the left eye and the other for the right. The converging lens forms the virtual image of the stereogram behind the actual display screen. When the CRT screen is 4.2 cm apart from the lens whose focal length is 5 cm, the virtual image of the CRT screen is formed at 25 cm apart from the lens with an image magnification of 6. Thus, a 1-inch CRT screen appears to be a 6-inch screen to the viewer. At appropriate geometrical and optical conditions, the right and left images overlay, and most people can fuse the two images into a single three-dimensional image. The stereoscopic display formulas used to generate the stereogram for the helmet mounted display are described in references (Kim, et al, submitted 1995).

Mechanical Design

Five degrees of freedom were provided for the mechanical adjustment of the position and orientation of each viewfinder, allowing three orthogonal slidings and two rotations (Figure 11). A 1 lb counterweight was attached to the back of the helmet for counterbalancing.
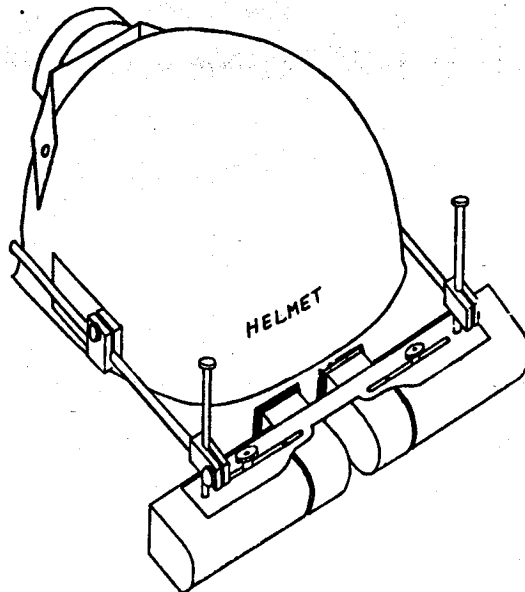
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HELMET

Figure 11. Current HMD Design: CRT screens provide stereo vision, with high resolution. Slave stereo camera could provide distant scene information in accordance with helmet pan and tilt; however we have so far used simulated stereoscopic scenes.

SUMMARY

The class experiments enabled our Telerobotic Unit at the University of California, Berkeley, to explore in a number of research directions. The HMD direction has now been greatly extended and is a major focus in our laboratory. On the other hand, the homeomorphic controller did not seem to be a productive project to continue because of the adaptability of the H.O. to many configurations of control. Also, our interest in supervisory and other high level controls is leading us away from direct manual control. The students were enthusiastic and felt the course stimulated their creativity and provided an opportunity for them to engage in relatively unstructured laboratory work---a good model for subsequent thesis research.

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